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Deep mixing technology to improve the bearing capacity of a very soft clayey soil under an earth embankment

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ABSTRACT: In the paper we are describing the Deep Mixing treatment carried out at Vicarello-Stagno site (near Livorno - Italy) where a road embankment had to be built in a very short time.
The foundation soil was constituted of a very soft clay (S_u less than 30 KPa down to 20 m depth); in those conditions the soil failure would occur under the weight of an embankment of a height of 3 m only.
It was necessary to execute the consolidation treatment of the foundation soil in order to limit the settlements of the embankment close to the abutements of two viaducts and around a crossing pipe line.
We relate about geotechnical investigation, comparison between Deep Mixing and other technologies, design criteria, technology adopted (Deep Mixing with dry cement), site operations description and settlement control apparatus. The reading of control device, up to october 1990, points out that the technology employed is satisfactory and in accordance with the aim of the design.

1. INTRODUCTION

The treatment of soil by the Deep Mixing technology is part of the work for the construction of the embankment of the Tora 2A extract of lot II of the highway which will connect Firenze, Pisa and Livorno.

The lot is situated between the villages Vicarello and Stagno in the borough of Collesalvetti (Livorno) where the river Tora meets the spillway channel of Arno.

The geological formation has origin from recent floodings of rivers and sea, mostly silty-clay nature.

The area in question is reclaimed land since the XIV century, when they tried to protect the area from the invading marsh; in fact we can find on the plain outcrops caused by reclaimed land of recent centuries.

Therefore the ground here is extremely compressible and saturated with water, where even the building of an embankment a few meters high, causes relevant settlements requiring a long time to consolidate.

In the design stage it was necessary to envisage a consolidation treatment of the foundation soil in order to limit as much as possible the settlements of the embankment near the abutment of the viaduct crossing the river Tora, of the embankment which leads to the new overpass of the motorway Firenze, Pisa, Livorno and where the methane pipe-line crosses the motorway itself (see figure 1).

The consolidation of the soil was in fact the only possible solution because, considering that the time required for the construction was extremely limited (6 months from the start of work up to the opening of the highway), we had to rule out solutions allowing important settlements and foreseeing further

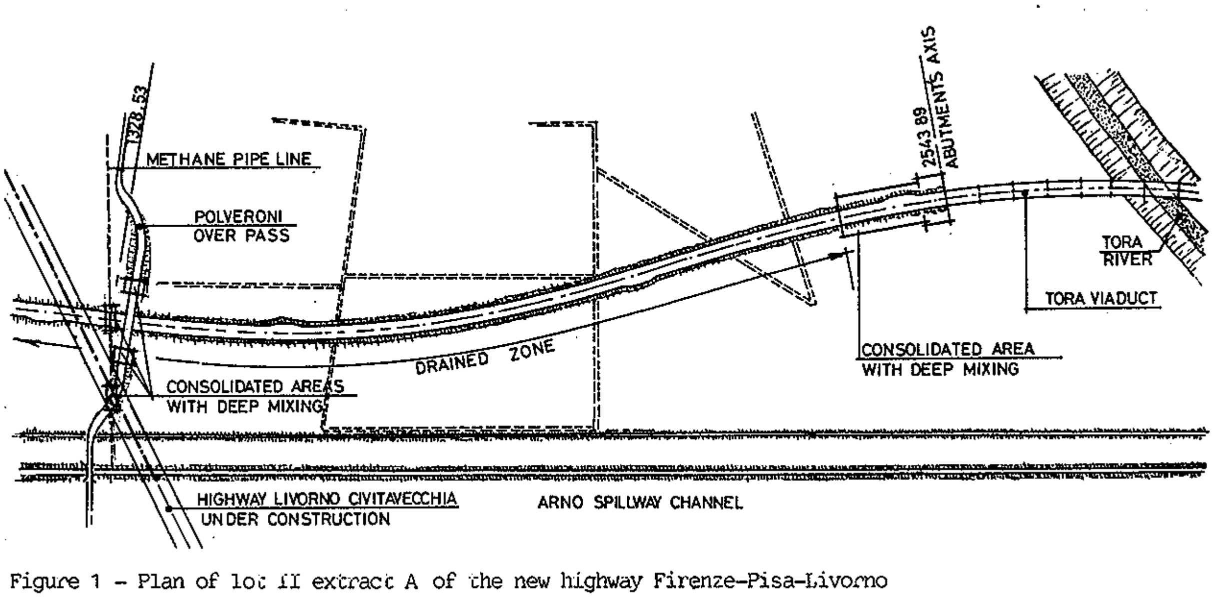

Figure 1 - Plan of lot II extract A of the new highway Firenze-Pisa-Livorno

reloadings to keep the original designed level.

Therefore we examined the following technologies in order to decide which one was the most suitable to resolve this situation

- porous concrete piles
- jet-grouting Ø 60 cm
- Deep Mixing Ø 100 cm
- vibrated sand or gravel piles.

Eventually we decided to adopt the Deep Mixing technology for the following reasons.

a) Owing to the very low mechanical properties of the soil, even where very deep, in order to limit settlements, it was necessary to consolidate the soil at least down to 20 m under the embankment.
So it was not advisable to use vibroflotation because the gravel or sand columns should have been too deep and also numerous.

b) For the treatment of the soil by means of more rigid columns, a global consolidation on the whole mass of soil treated can be envisaged only with a distance between the columns of not more than 3-3,5 times the diameter of the columns themselves.
This is not connected with the characteristics of resistance of the columns compared with those of the soil.
The solution by means of porous concrete piles or of jet-grouting would therefore have involved many more columns (one concrete pile per 1 m^2 and one column of jet-grouting approximately per $3m^2$) which would have meant a much higher cost than that of the Deep Mixing.

c) In the deep mixing technology, the water used for the hydration reaction and the cement dust are mixed in the soil, and should the soil be saturated, part of the water would be used directly for the hydration reaction.
This involves a reduction of the percentage of water present in the soil, which should theoretically speed up the process of consolidation.

Moreover, which is rather interesting, we believed it would be of great interest to study the behaviour of clay and silty clay consolidated by Deep Mixing.

In fact in Italy this new technology has been used before only for the treatment of the dump residue obtained from the working of a lignite quarry.

For this purpose, both in the consolidated area near the abutment of Tora viaduct and the drained one nearby, a control device system has been installed, in order to check settlements of the two different areas.

Furthermore samples have been taken from the consolidated columns to carry out laboratory tests.

In the case of areas far from the concrete structures and therefore allowing more relevant settlements, we have installed geodrains 17 m long in a layout of 1m x 1m.

In the following chapters we explain the Deep Mixing technology, we relate the more interesting data concerning the preliminary investigations, the design phase, the site and the results of the laboratory tests carried out on the consolidated ground.

We also show the diagrams of the settlements recorded up to now (october 1990), both in the consolidated area and in the drained one, and we compare them with the data calculated during the design phase.

2. DEEP MIXING TECHNOLOGY

The method consists in improving the characteristics of soft or loose soils by means of a mechanical mixing process which thoroughly mixes the soil in situ with the stabilizing agents, in powder or granular form, plus any additives or aggregates, introduced using the dry feed method (pneumatic feed).

The stages of the process (see figure 2) include a drilling operation, during which the soil is disgregated, followed by the raising of the cutting blades under reverse rotation, at a predetermined rotation and lift speed, with the simultaneous feed of the binding agent.

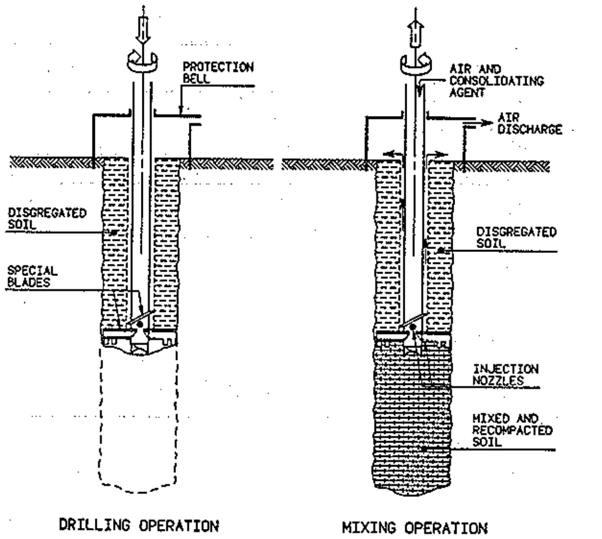

Figure 2 – Scheme of Deep Mixing method

The particular shape of the blades ensures the uniform distribution of the consolidating agent and the recompacting of the disgregated and mixed soil.

In addition, the geometry of the blades and the kelly and the use of a protection bell ensure the expulsion, at the mouth of the hole, of air alone, preventing pointless wastage of the binding agent.

At present, consolidated soil columns with a diameter of 800-1000 mm have been achieved using single and twin head rigs (see figure 3).

3. GEOTECHNICAL INVESTIGATIONS

Before the planning of the work, two exploratory campaigns were carried out, the first by ANAS concerning lot II and the second by SGF Company in the areas of the viaducts.

In addition to the stratigraphy obtained through exploratory borings, the following data were available: the results of some SCPT, SPT, permeability tests in situ, executed in the exploratory holes, grain size analysis, Atterberg limits and unit weights, results of edometric tests, of direct simple shear tests and of triaxial compression tests.

Moreover, in the areas of the embankment and foundations of Tora viaduct, static penetrometric tests down to a depth of 60 m had been carried out.

The soil stratigraphy consists of a first layer

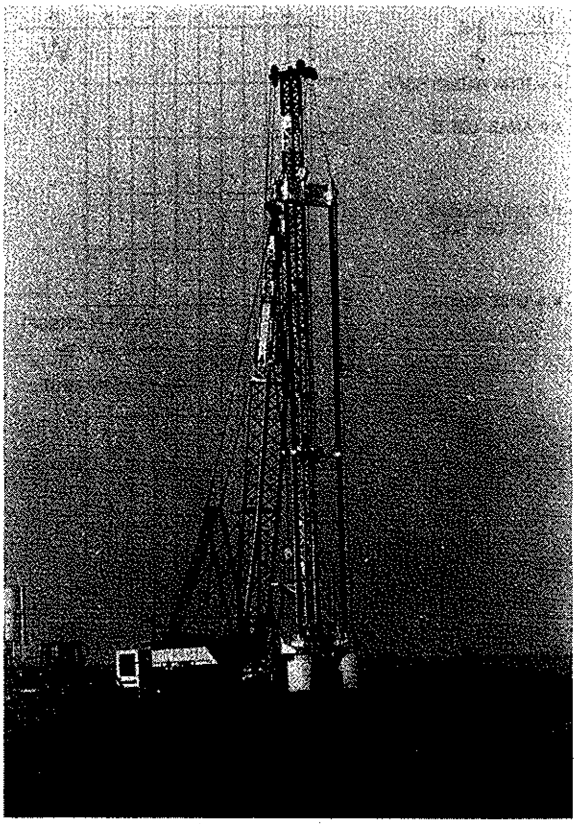

Figure 3 - Soil Mec for Deep Mixing construction, EC50 special model with twin head rigs

mainly clayey over consolidated by a drying process down to a depth of approximately 5 m, followed by clayey silts or clays with fluid-plastic consistency (water content up to 60% in the first 20 m) down to a depth of around 45 m; in this second formation lenses 2-3 m thick of more permeable sandy silts can often be found.

Only below 45 m depth, we come across stiff sandy silty soils.

In order to obtain a complete view of the characteristics of the embankment foundation soils, all the most important parameters available (E, Su, γ, Wn, Wl, Wp, PI, IC) have been plotted according to their depth.

As we can observe in fig. 4, the data obtained in the two exploratory campaigns resulted nearly homogeneous; therefore in the choice of the particular parameters of each layer, we referred to the average values, taking into account the results of all the tests.

As to edometric E modulus, in clay or silty clay, the following average values have been obtained:

from 0 to 10 m	E = 0,77 MPa
" 10 to 15 m	E = 1,0 "
" 15 to 25 m	E = 2,66 "
" 25 to 45 m	E = 3,33 "
beyond 45 m	E = 5,5 "

Moreover, where the exploration stratigraphy showed a high percentage of sand, we adopted E = 3,125 MPa above 15 m and E = 7,7 MPa below a depth of 15 m.

In order to have an estimate of the times of consolidation, the following values of the consolidation coefficient (cv) have been used

for clay $cv = 10^{-4}$ cm^2/s
for clayey silt $cv = 10^{-3}$ "

For sandy silt and sand, instead, we have envisaged an immediate settlement.

4. THE DESIGN PHASE

In the planning of consolidation works, we had to take into consideration the fact that, in such a compressible soil, when the embankment is high, there may exist problems of bearing capacity or stability.

Therefore the consolidation is necessary not only to limit the settlement, but also to stabilize the whole clayey foundation mass.

For this purpose we have calculated the bearing capacity of the soil in undrained conditions.

Referring to the solution of Prandtl, for a value of the strength of 20 KPa, we obtained a bearing capacity of 102,8 KPa.

Therefore we decided to execute the consolidation at least in the areas where the embankment was more than 2,5-3 m high, so that a safety coefficient for this failure mechanism of 1,5-2 was reached.

As for the partial failure mechanism of the embankment slope, we carried out stability analysis in undrained conditions with an undrained shear strength value of 20 MPa.

In figure 5 we show the most critical sliding surface obtained for an embankment 3,5 m high.

Having considered the results of the analysis above mentioned, the consolidation has been executed from the abutment of Tora viaduct, over a length of 148 m, where the embankment height varies between 2,7 m and 4 m.

The pattern of the columns has been planned considering the unconfined compressive strength of the columns themselves, that is 0,25 MPa, and their diameter.

In the area close to the abutment, where the embankment is more than 3,3 m high, the columns are 3 m apart from one another in the two directions; where the embankment is lower the columns are 3 m apart in one direction and 3,2 m apart in the other one.

Furthermore we must remember that the geometric pattern of the columns depended on the machine employed, which, as shown in figure 3, operated simultaneously the two twin mixing rods fixed at a distance of 3 m one from the other.

As for the depth of the treatment, we must point out that any work executed at a depth inferior to 40-45 m would cause greater settlements than those envisaged for viaduct structures founded on piles 50-60 m long.

We had therefore to find a compromise between these factors:

- to control settlements near the abutment
- to keep down the costs of the work
- do not exceed the depth reached by the mixing rods.

It was furthermore necessary not to cause a relevant discontinuity between the embankment area founded on consolidated soil and on the drained one.

In figure 6 we can note that the depth of the columns varies from a maximum of 22 m (length of the mixing rods) to a minimum of 12 m.

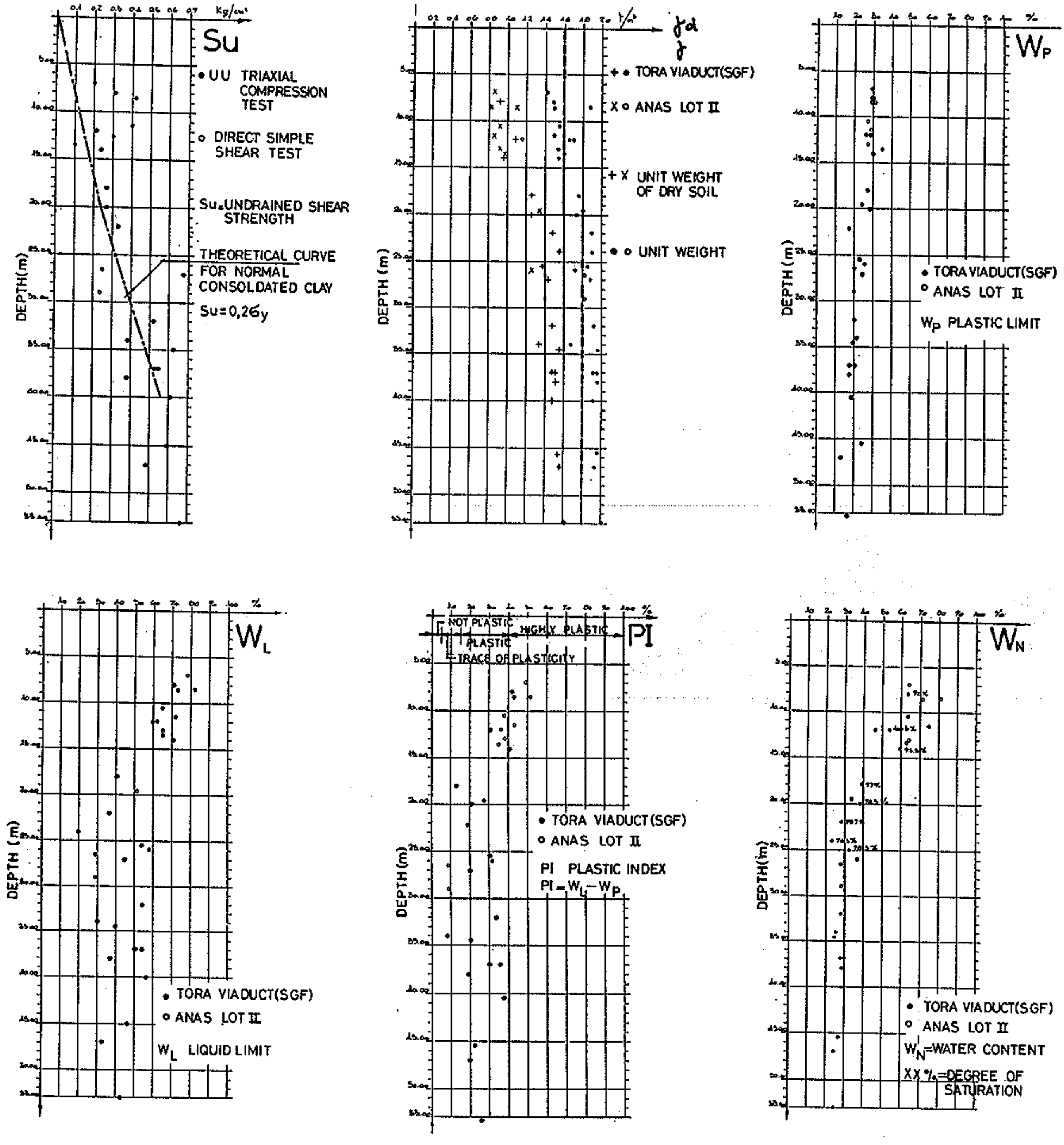

Figure 4 – Soil investigation data: unit weight, water content, Atterberg limits and undrained shear strength

C	X	Y	R	Fs
1	3,0	6,0	12,26	1,24
2	3,0	5,0	10,11	1,20
3	3,25	4,75	7,85	1,13
4	3,5	4,5	5,59	117
5	2 5	4 0	4 53	127

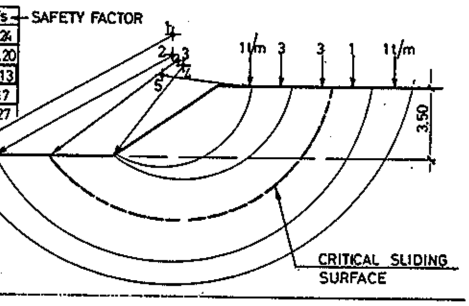

Figure 5 – Stability analysis of the embankment

We then calculated the settlements for different heights of the embankment, both in unconsolidated and drained areas and in the consolidated ones.

We followed the method of Terzaghi, that is we calculated the vertical stress increments at the different depths and consequently the settlments involved by elasticity parameters resulting from the edometric tests.

In order to evaluate the increase of vertical stresses, we considered that stresses were spreading according to an angle of about 26°, that is 0,5 m per meter of depth: besides we left out the ones inferior to 10% of the stresses value in situ before the embankment construction.

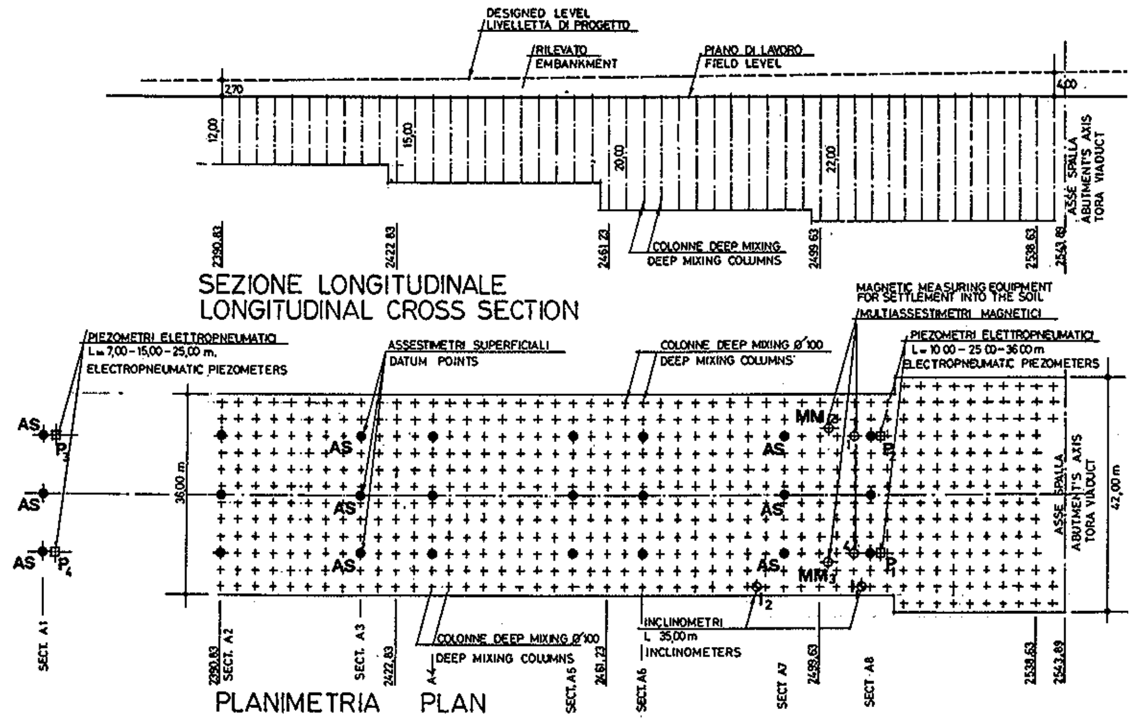

Figure 6 - Layout of the Deep Mixing treatment near Tora Viaduct and of the site control instrumentation

While calculating the settlements of the embankment, we neglected the settlement of the Deep Mixing consolidated volume because we believed it was not important comparing it to the one of the soil below.

In table one we show the final values of the settlements foreseen both for the soil consolidated with Deep Mixing and for the soil without consolidation (treatment with geodrains).

Table 1

Embankment height(m)	1,5	2,5	2,5	3,0	3,5	4,0
Settlement in drained zone (cm)	59	87	87	98	114	125
Depth of columns (m)	-	12	15	20	22	22*
Settlement in consolidated zone (cm)	-	33	25	26	32	33

* The width of the consolidation area is 42 m instead of 36 m as in the other cases.

The calculation of the times of consolidation turned out more complex as far as the consolidated area is concerned.

It was difficult to establish the drainage path; we assumed that the water could drain only in the more permeable layers of sandy silt or sand situated below the consolidated area.

The depth and thickness of these layers has been determined by the stratigraphy found in a typical esploratory bore hole.

Since the times of consolidation are inversely proportional to the square of the drainage path, it is evident that the supposed location of the permeable layers and the assumption that water cannot flow in the consolidated volume, has highly affected the evaluation of the consolidation time.

Figure 7 shows the curves of the consolidation calculated both in the consolidated area and in the drained one.

5. THE SITE

In all, we have executed 15.120 m of Deep Mixing columns, distributed over two areas of approximately 40m x 200m each.

Therefore, half way through the work, we had to move the drilling rig and the pumping station to the second position.

For the columns we used Portland cement 425 and 325 in a quantity of about 2300 N per meter of column, equal to 2900 N per cubic meter of soil.

In the phase of maximum work, 3 shifts of eight hours per day took place and the average production of the site (excluding the periods of equipment assembling, moving and dismantling) was of 108 m/per shift with a total of 140 shifts of work.

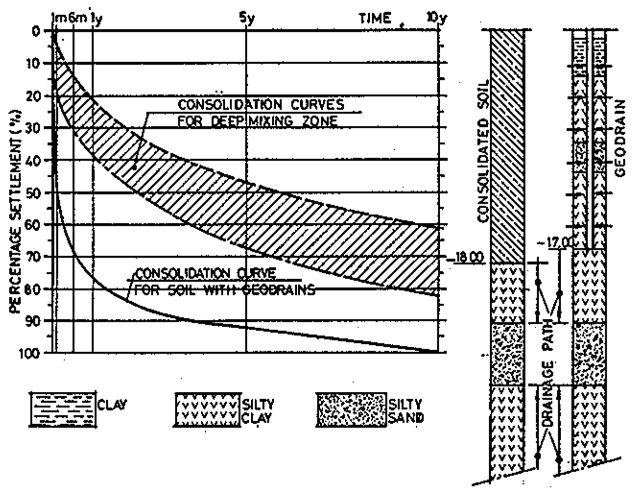

Figure 7 - Theoretical consolidation curves in drained and consolidated areas

In the last phase of the work, owing to changes and improvements to the equipment, the production was of 139 m/per shift (17,4 m/h).

6. CONTROL DEVICE SYSTEM

In the consolidated area close to the abutment of the Tora viaduct, we set up a more sophisticated and numerous equipment compared with the one installed in the other part of the embankment.

In fact in the drained area, only datum points were placed to check the surface settlements.

In each equipped section, three datum points were located of which one at the road axis and the other two at the sides.

The equipment for the Deep Mixing area was chosen so as to give information about the following items:

1. development and quantity of settlements
2. development of excess pore pressures in the foundation soil
3. buckling of Deep Mixing columns
4. horizontal movements of the foundation soil.

In figure 6 we illustrate the location of the equipment installed in the consolidated area and in the drained one close to it.

They are

n. 4 magnetic measuring equipment for settlements, two of which are set up inside the columns and the other two in the soil between the columns

n. 2 vertical inclinometers installed near a lateral slope of the embankment at a distance of 19 m one from the other

n. 4 electropneumatic piezometers, two of which located in the consolidated area and two in the drained one.

We equipped the consolidated area with more precision than usual because this was the first experience of application of Deep Mixing method in this kind of soil.

Moreover we envisaged carrying out cores inside some consolidated columns, from which we took samples for laboratory tests in order to find out the unconfined compressive strength and E modulus of elasticity.

7. CHECKS ON FIELD AREA

The checks performed on the field area included:

- vertical core borings through 2 columns with the drawing out of samples for laboratory tests
- excavation of an exploratory shaft for visual inspection of the treatment.

a) Vertical checking holes

Two months after execution, 2 vertical core holes were executed coaxially with 2 treated soil columns.

The samples taken during coring were subjected, in the laboratory, to unconfined compressive tests.

Figure 8 shows the strength values obtained from the tested soil samples.

We can note that the average value is the same as the one foreseen in the design, that is 2,5 MPa.

b) Inspection shaft

A square section inspection shaft, measuring 10 m per side, was excavated at a depth of 3 m from ground level.

The shaft is shown in figure 9.

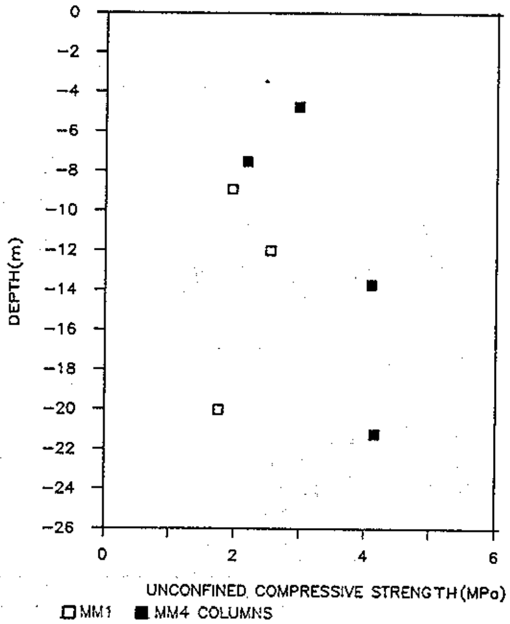

Figure 8 - Strength characteristics from laboratory tests on samples recovered in direction parallel to the axis of the columns

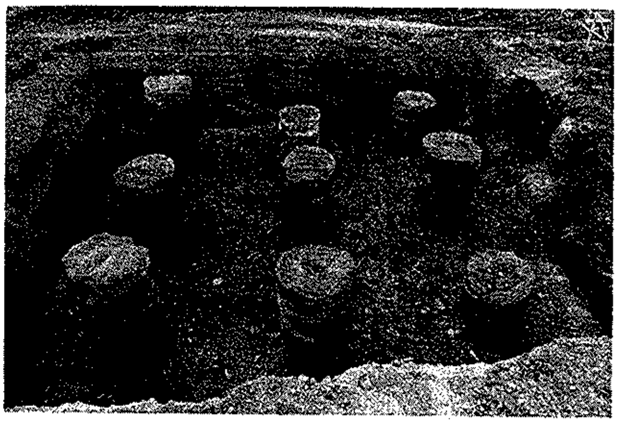

Figure 9 - View of the inspection shaft and of the Deep Mixing column heads

The aims of the shaft were principally the following:

- checking by visual inspection of the 9 columns involved in the excavation
- verifying the reliability of the Deep Mixing column treatment method and the effective diameters obtained.

8. READING OF CONTROL DEVICES

Here below we describe the first readings executed from March to October 1990.

In figure 10 we report the average soil settlements regarding all equipped sections, and in figure 11 the average settlements of each equipped section versus time (consolidation curves).

We can notice that the most relevant settlements occured in the drained area in the direction of the Tora river, between the chainages 1400 and 2400,

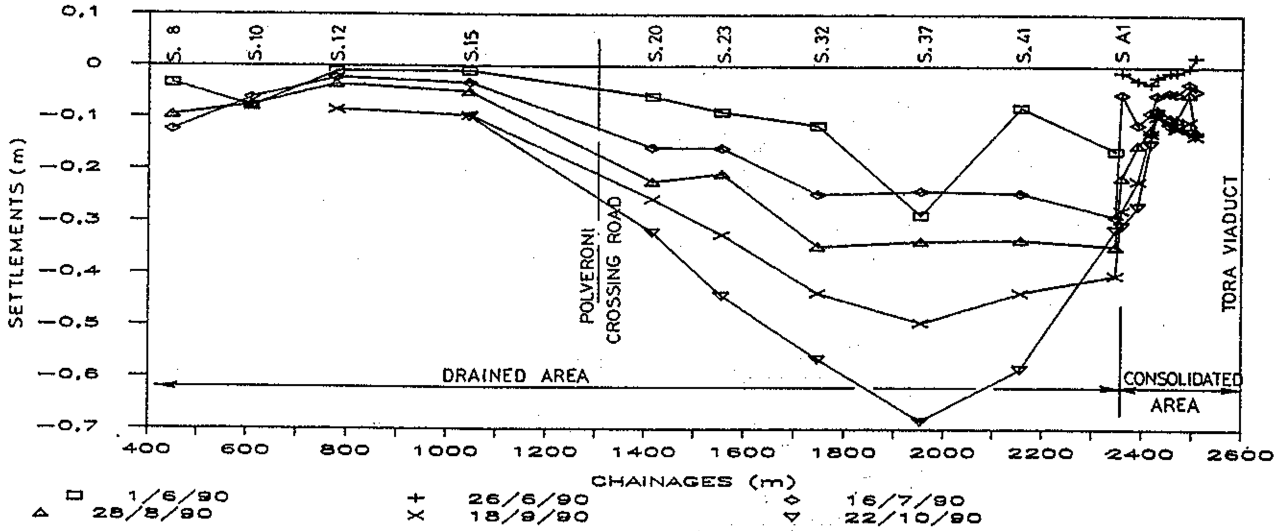

Figure 10 – Settlements measured in all sections equipped with datum points (up to October 1990)

that is in the area situated between the end of the consolidation by Deep Mixing close to the abutment of the viaduct and the new crossing of the Polveroni road.

We want to point out that the whole embankment in the drained area has a more or less constant height, around 2,5 m, while the settlements are lower in the first part of the lot (up to chainage 1400).

This is due to the fact that as we approach the river Tora, clays loose their strength and silts become mostly clayey, resulting in an increase of soil compressibility.

The settlements of the consolidated area (Deep Mixing) are very low in spite of the relevant compressibility of the clayey soil.

In figure 11 it is interesting to notice the difference between the consolidation curves of the drained area and those of the consolidated one.

In fact we can observe that the former ones are still very steep and do not show any slowing down of the consolidation speed: the latter instead are becoming flatter.

We can therefore already evaluate the great difference of behaviour between the two treatments under the embankment with regard to the speed of consolidation, while it is too early to compare the theoretic consolidation curves with the ones measured, because the construction of the embankment is too recent.

In figure 12 we report the settlements measured at the different depths by the magnetic measuring equipment M1 and M2, located in the consolidated area with columns 22 m deep.

Pipe M1, located among 4 columns, measures settlements down to 38 m of depth; M2 measures only settlements occured inside a consolidated column.

In the case of all the magnetic instrumentation equipment, including M3 (M4 is no longer in use) the amount of global settlements is approximately equal to the ones obtained in the datum point survey, that is about 15-20 cm.

The most relevant data obtained from these measurements at different depths are:

- against the prevision, the deformation of the volume of the consolidated soil, at least in this first period. does not seem to be insignificant compared to that of the soil below, since it is about 30% of the whole; from the future readings we will notice if in this consolidated area the

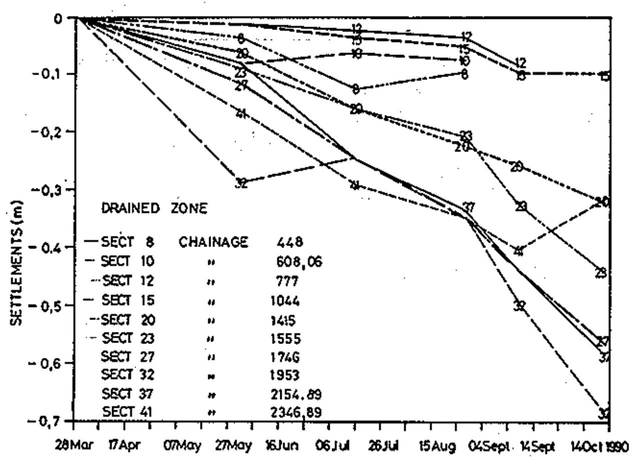

Figure 11a – Settlements versus time obtained in the drained zone

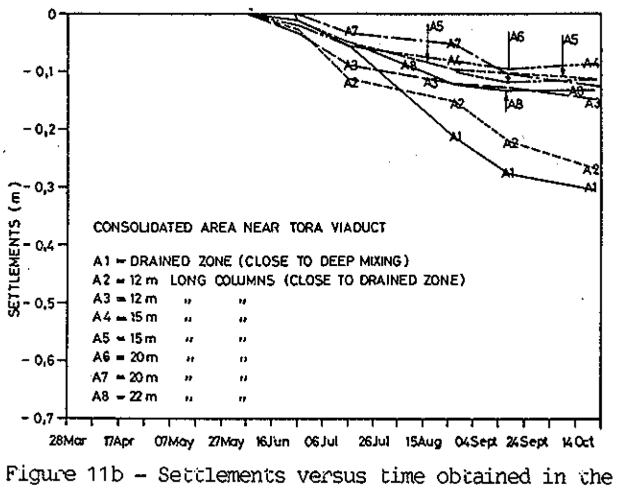

Figure 11b – Settlements versus time obtained in the consolidated zone

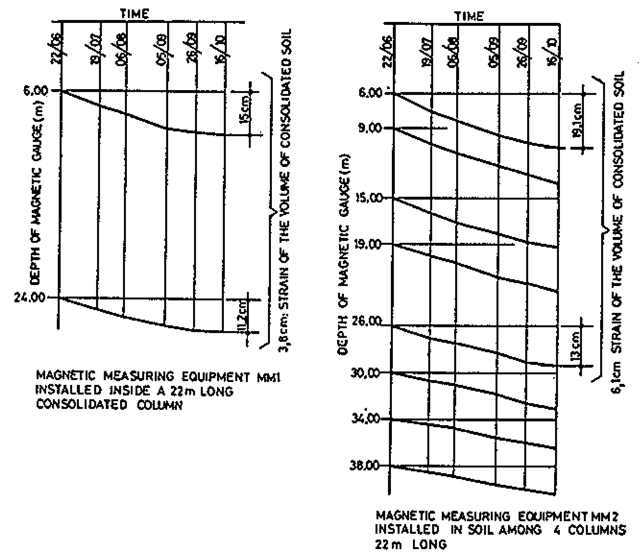

Figure 12 - Settlements measured at different depths in the magnetic measuring equipment MM1 and MM2

settlements will disappear quicker than in the deeper zones

- the settlement of the consolidated area, measured within the columns or outside, is pratically the same, that means that the distance between the columns is the right one to consolidate homogeneously the whole volume of the soil.

The values measured by this equipment could be used to evaluate modulus of elasticity of all the consolidated area and then compared with the modulus of the columns obtained through laboratory tests.

As for inclinometric readings, except the two or three meters on the surface where we can measure a

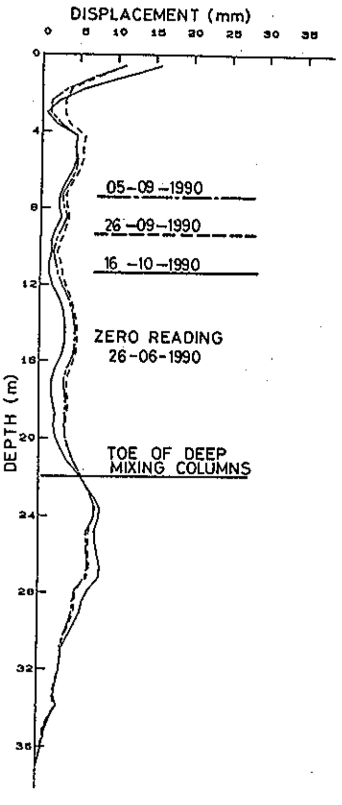

Figure 13 - Inclinometer readings of instrument S1

horizontal displacement of 15 mm, in the whole consolidated area, the displacement is constant and approximately equal to 5 mm (see figure 13).

This means that the consolidated volume is rigid enough to prevent significant lateral deformations due to loading.

Unfortunately it is not possible to compare these measurements with those of the drained area: in fact we preferred to install two inclinometers in the consolidated area in order to prevent a possible breaking of a single instrument.

The piezometer readings of the 4 instruments installed show, up to now, a regular decrease of the excess pore pressure in accordance with the normal behaviour of the consolidation process.

9. CONCLUSION

It is probably premature to give a definitive judgment on the effectiveness of the consolidation work executed with columns by means of the Deep Mixing technology.

Neverthless all the results, up to now, point out that the technology employed is very satisfactory and in accordance with the aim of the design.

In this respect it is interesting to observe in the graph of figure 10 the relevant decrease of the settlements in the consolidated area compared to those in the drained one.

The results of laboratory tests have confirmed the unconfined compressive strength values envisaged in the design for the columns treated.

Furthermore we observed that the consolidated soil undergoes small settlements and that the lay out of the pattern of the columns is suitable, because the reaction of the soil is homogeneous. We do not notice important differences of settlement between the columns and the soil around them.

It was a very interesting experience for all the ones who worked on the project, since we applied here a new and little known technology, which had not been tested before in such a compressible clayey soil.

It is therefore now very important to obtain the greatest number of data from the readings of the control device system and from the future observation of the embankment behaviour, with the aim to have a complete outline of data for other designs in soils having the same characteristics.

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